THE CRYOGENIC WIND TUNNEL

Robert A. Kilgore
NASA Langley Research Center

SUMMARY

Based on theoretical studies and experience with a low-speed cryogenic tunnel and with the Langley 1/3-meter transonic cryogenic tunnel, the cryogenic wind-tunnel concept has been shown to offer many advantages with respect to the attainment of full-scale Reynolds number at reasonable levels of dynamic pressure in a ground-based facility. The unique modes of operation available in a pressurized cryogenic tunnel make possible for the first time the separation of Mach number, Reynolds number, and aeroelastic effects. By reducing the drive-power requirements to a level where a conventional fan-drive system may be used, the cryogenic concept makes possible a tunnel with high productivity and run times sufficiently long to allow for all types of tests at reduced capital costs and, for equal amounts of testing, reduced total energy consumption in comparison with other tunnel concepts.

1. INTRODUCTION

Present interest in the development of transports and maneuvering aircraft to operate efficiently in the transonic range has resulted in a review of the problem of flow simulation in transonic wind tunnels. Among the more serious problems is that related to inadequate test Reynolds number. It is this problem and an attractive solution to the problem that is the subject of this paper.

The need for increased testing capability in terms of Reynolds number has been well documented. (See, for example, refs. 1 and 2.)

At a given Mach number, the Reynolds number may be increased by using a heavy gas rather than air as the test gas, by increasing the size of the tunnel and model, by increasing the operating pressure of the tunnel, and by reducing the test temperature. The method chosen to increase Reynolds number will, in general, also affect dynamic pressure, mass flow rate, and the energy consumption of the tunnel for a given amount of testing.

The use of a heavy gas is a well-known method of achieving high Reynolds number. Freon-12 is one of the most suitable of the heavy gases for use in a wind tunnel (ref. 3). However, the differences in the ratio of specific heats become important when compressibility effects become significant, thus making Freon-12 a questionable transonic test gas (ref. 4).

An obvious way to increase Reynolds number is to increase the model size. In order to avoid increasing the wall interference effects, however, there must be a commensurate increase in tunnel size. Design studies for tunnels large enough to give full-scale Reynolds number at normal temperatures and moderate

pressures show that they would be very large, and therefore very costly, and would make heavy demands on power (ref. 5). An alternate solution is to restrict the tunnel and model sizes and increase the operating pressure. This method is feasible, of course, but the aerodynamic forces on the model, balance, and support system are greatly increased at the operating pressures that are required to achieve the desired Reynolds number in a tunnel of moderate size. From a power standpoint, a high-pressure tunnel is preferable to a large, moderate-pressure tunnel. However, for the required increase in Reynolds number, the power requirements are still undesirably large.

Operating a tunnel at cryogenic temperatures, first proposed by Smelt (ref. 6) in 1945, offers an attractive means of increasing Reynolds number while avoiding many of the practical problems associated with testing at high Reynolds numbers in conventional pressure tunnels. Personnel of the NASA Langley Research Center have been studying the application of the cryogenic concept to high Reynolds number transonic tunnels since the autumn of 1971. The results of a theoretical investigation aimed at extending the analysis of Smelt and the results of an experimental program using a low-speed wind tunnel have been reported in references 7 and 8. In order to provide information required for the planning of a large high Reynolds number transonic cryogenic tunnel, as described in reference 9, a relatively small pressurized transonic cryogenic tunnel was built and placed into operation in 1973. As a result of the successful operation of the pilot transonic tunnel, it was classified by NASA in late 1974 as a research facility, re-named the Langley 1/3-meter transonic cryogenic tunnel, and is now being used for aerodynamic research as well as cryogenic wind-tunnel technology studies.

In addition to reviewing the cryogenic wind-tunnel concept, this paper presents some details of the design and operation of the Langley 1/3-meter transonic cryogenic tunnel and describes some of the research done in the tunnel related to validation of the cryogenic wind-tunnel concept. Also presented are the future plans for the 1/3-meter tunnel.

A new fan-driven high Reynolds number transonic cryogenic tunnel is being planned for the United States. This tunnel, to be known as the National Transonic Facility, will take full advantage of the cryogenic concept to provide an order of magnitude increase in Reynolds number capability over existing tunnels. Details of this new facility will be given in a subsequent paper by D. Baals.

2. SYMBOLS

a Speed of sound

c Chord of two-dimensional airfoil

$\bar{c}$ Mean geometric chord

C_D Drag coefficient, $\frac{\text{Drag}}{qS}$

C_L	Lift coefficient, $\frac{\text{Lift}}{qS}$
C_m	Pitching-moment coefficient, $\frac{\text{Pitching moment}}{qS\bar{c}}$
C_p	Pressure coefficient, $\frac{p - p_\infty}{q_\infty}$
ℓ	Linear dimension of model
M	Mach number
p	Pressure
q	Dynamic pressure, $1/2\ \rho V^2$
R	Reynolds number, $\rho V \ell / \mu$
S	Reference wing area
T	Temperature
V	Velocity
x	Linear dimension
α	Angle of incidence
μ	Viscosity
ρ	Density

Subscripts:

max	Maximum
min	Minimum
t	Stagnation conditions
∞	Free stream

3. THE CRYOGENIC CONCEPT

The use of low temperatures in wind tunnels was first proposed as a means of reducing tunnel drive-power requirements at constant values of test Mach number, Reynolds number, and stagnation pressure. Reynolds number, which, of course, is the ratio of the inertia force to the viscous force, is given by

$$R = \frac{\text{Inertia force}}{\text{Viscous force}} = \frac{\rho V^2 \ell^2}{\mu V \ell}$$

which reduces to the well-known equation

$$R = \frac{\rho V \ell}{\mu} = \frac{\rho M a \ell}{\mu}$$

As the temperature is decreased, the density ρ increases and the viscosity μ decreases. As can be seen from the above equations, both of these changes result in increased Reynolds number. With decreasing temperature, the speed of sound a decreases. For a given Mach number, this reduction in the speed of sound results in a reduced velocity V which, while offsetting to some extent the Reynolds number increase due to the changes in ρ and μ, provides advantages with respect to dynamic pressure, drive power, and energy consumption.

It is informative to examine the underlying mechanism through which changes in pressure and temperature influence Reynolds number. To the first order μ and a are not functions of pressure while ρ is directly proportional to pressure. Thus, increasing pressure produces an increase in Reynolds number by increasing the inertia force with a commensurate increase in model, balance, and sting loads. Also, to the first order, $\rho \propto T^{-1}$, $V \propto T^{0.5}$, and $\mu \propto T^{0.9}$. Thus, decreasing temperature leaves the inertia force unchanged at a given Mach number due to the compensating effects of ρ and V^2. The increase in Reynolds number with decreasing temperature is thus due strictly to the large reduction in the viscous force term as a result of the changes in μ and V with temperature.

The effect of a reduction in temperature on the gas properties, test conditions, and drive power are illustrated in figure 1. For comparison purposes, a stagnation temperature of 322 K (+120° F) for normal ambient temperature tunnels is assumed as a datum. It can be seen that an increase in Reynolds number by more than a factor of 6 is obtained with no increase in dynamic pressure and with a large reduction in the required drive power. To obtain such an increase in Reynolds number without increasing either the tunnel size or the operating pressure while actually reducing the drive power is extremely attractive and makes the cryogenic approach to a high Reynolds number transonic tunnel much more desirable than previous approaches.

3.1 The Advantages of a Cryogenic Tunnel

3.1.1 Reduced Dynamic Pressure and Drive Power

For a selected tunnel size and Reynolds number the previously described effects of cryogenic operation are manifested in large reductions in the required tunnel stagnation pressure and, therefore, in large reductions in both the dynamic pressure and the drive power. These reductions are illustrated in figure 2, where both dynamic pressure and drive power are shown as functions of

stagnation temperature for a constant chord Reynolds number* of 50×10^6 at $M_\infty = 1.0$ for a tunnel having a 2.5- by 2.5-m test section. As the tunnel operating temperature is reduced, the large reductions in both dynamic pressure and drive power are clearly evident and provide the desired relief from the extremely high values that would be required for a pressure tunnel operating at normal temperatures. Some of the specific advantages resulting from the reduction in dynamic pressure include reduced model and balance stresses, with the resulting increased test lift coefficient capability, reduced sting size for a given lift which reduces sting interference and permits more realistic aft fuselage modeling, and an increased stress margin for aeroelastic matching.

The large reduction in drive power makes a fan-driven tunnel practical even at this high Reynolds number. The resulting efficiency and increased run time provide important advantages relative to intermittent tunnels, such as increased productivity, improved dynamic testing capability, and reduced operating costs and total energy consumption for equal amounts of testing.

An additional advantage of a fan-driven tunnel is realized by having run times sufficient to insure the avoidance of problems caused by heat transfer between the model and the stream. In tunnels where the flow is generated by expansion waves, spurious scale effects due to heat transfer can only be avoided by cooling the model to the expected recovery temperature (ref. 3). Such problems are avoided in a continuous-flow tunnel where the model is never far from thermal equilibrium with the stream. In general, no additional testing time is required to allow the model to achieve thermal equilibrium since the flow initiation process is gradual and test conditions are not changed abruptly in a fan-driven tunnel.

The advantages of the cryogenic concept with respect to reduced dynamic pressure and reduced drive power are shown in figure 2 for constant Reynolds number and constant test-section size. For a constant tunnel size, both the shell costs, which may account for as much as two-thirds of the total cost of a wind tunnel, and the costs of the drive system for the tunnel vary nearly linearly with the maximum stagnation pressure of the tunnel. Therefore, for conditions of constant Reynolds number and tunnel size, the reduction in the stagnation pressure which is needed to achieve the desired Reynolds number at cryogenic temperatures results in a reduction in capital costs even when the higher costs of the structural materials which are suitable for use at cryogenic temperatures is taken into account.

If the attainment of increased Reynolds number is accomplished by increasing stagnation pressure, for many configurations a pressure limit is reached beyond which the loads on the model will preclude testing at the desired lift coefficient. With this in mind, an alternate approach to the design of a high Reynolds tunnel is to establish the maximum usable pressure and allow tunnel size to decrease with design temperature in order to attain the desired Reynolds

*For consistency throughout this paper, Reynolds number is based on a wing chord equal to 0.1 times the square root of the test-section area; for wings of small aspect ratio the actual values may be two or three times the value given.

number. Under these conditions, there is a very strong impact of the cryogenic concept on capital cost due to the large reduction in tunnel size required for the attainment of a given Reynolds number.

At a constant pressure, the cost of the tunnel shell varies approximately with the cube of the tunnel size, whereas the cost of the drive system varies approximately with the square of the tunnel size. Thus, a reduction in tunnel size by a factor of 5 or 6, which, as can be inferred from figure 1, may be realized by operating at cryogenic temperatures, represents a substantial savings in capital costs over the much larger ambient-temperature tunnel which would be required to achieve the desired Reynolds number at the same stagnation pressure.

3.1.2 Reduced Peak Power Demand and Total Energy Consumption

Because of the high peak power demands of large ambient-temperature transonic tunnels, the tunnel designer has, up until now, been forced to abandon the conventional continuous-flow tunnel and adopt some form of intermittent tunnel using energy storage techniques. However, since a fan is the most efficient method of driving a tunnel, the reduction in peak power demand obtained by going to conventional energy storage techniques is realized only by accepting an increase in total energy consumption. By reducing the drive power requirements to a level where a fan drive again becomes practical even for large tunnels, the cryogenic concept makes available not only the many technical advantages of the conventional continuous-flow tunnel but, at the same time, results in significant reductions in the total energy consumed during a test for a given Reynolds number and stagnation pressure (ref. 9). This reduction in total-energy requirement which results from cryogenic operation is especially significant in this age when the conservation of energy is assuming increasing importance.

3.1.3 Unique Operating Envelopes

In addition to the advantages of reduced dynamic pressures and reduced drive-power and energy requirements, the cryogenic wind-tunnel concept offers the aerodynamic researcher some unique and extremely useful operating envelopes. For a given model orientation, any aerodynamic coefficient is a function of, among other things, Mach number M, Reynolds number R, and the aeroelastic distortion of the model, which is, in turn, a function of the dynamic pressure q. A cryogenic tunnel with the independent control of Mach number, temperature, and pressure has the unique capability to determine independently the effect of Mach number, Reynolds number, and aeroelastic distortion on the aerodynamic characteristics of the model.

To illustrate the manner in which this is accomplished, a constant Mach number operating envelope is presented for a cryogenic transonic pressure tunnel having a 2.5- by 2.5-m test section. The main purpose of presenting the envelope is to illustrate the unique testing capability available in a cryogenic tunnel. However, the size of the tunnel and the ranges of temperature, pressure, and Mach number have been selected to represent the anticipated characteristics of the proposed National Transonic Facility.

The constant Mach number operating envelope showing the range of dynamic pressure and Reynolds number available for sonic testing is presented in figure 3. The envelope is bounded by the maximum temperature boundary (taken in this example to be 340 K), the minimum temperature boundary (chosen to avoid saturation at free-stream conditions), the maximum pressure boundary (8.8 atm), and the minimum pressure boundary (0.5 atm). With such an operating capability, it is possible, for example, to determine at a constant Mach number the true effect of Reynolds number on the aerodynamic characteristics of the model without having the results influenced by changing model shape due to changing dynamic pressure, as is the case in a conventional pressure tunnel. (There will be a slight variation of the modulus of elasticity E of most model materials with temperature. To correct for this variation in E, the dynamic pressure q may be varied by varying total pressure so that the ratio q/E remains constant over the Reynolds number range.) This ability to make pure Reynolds number studies is of particular importance, for example, in research on the effects of the interaction between the shock and the boundary layer. As indicated on the envelope, pure aeroelastic studies may be made under conditions of constant Reynolds number. In addition, combinations of R and q can be established to represent accurately the variations in flight of aeroelastic deformation and changes in Reynolds number with altitude. Similar envelopes are, of course, available for other Mach numbers. In addition to the constant Mach number operating envelope, two other types of envelopes are available in a pressure tunnel capable of cryogenic operation. These are the constant Reynolds number envelope and the constant dynamic pressure envelope. These envelopes have been described elsewhere (ref. 8) and will not be discussed further in this paper. From the aerodynamic research point of view, the most attractive feature of the cryogenic tunnel is the ability to isolate and study independently the effects of Reynolds number, Mach number, and aeroelasticity. The ability to isolate these effects is extremely desirable, since both aeroelasticity and Reynolds number can produce profound effects on critical aerodynamic phenomena, such as shock boundary-layer interactions.

3.2 Real-Gas Studies

In the cryogenic tunnel concepts developed at Langley, the test gas is nitrogen rather than air. Since 1972, an extensive study has been made by researchers at Langley to evaluate any possible adverse real-gas effects on aerodynamic data taken at cryogenic temperatures. The studies have been divided into two parts. The first part has looked at the effect of thermal and caloric imperfections on the isentropic expansion and normal-shock flow properties for the real gas, nitrogen, as compared to an ideal diatomic gas. These studies have shown that for pressures up to 5 atmospheres or so the behavior of nitrogen at cryogenic temperatures can be considered to be the same for all practical purposes as the behavior of an ideal gas. Portions of this part of the real-gas studies have been reported in reference 10 and will not be discussed further in this paper.

The second part of the real-gas studies has been concerned with determining the minimum usable stagnation temperature. When testing at cryogenic temperatures, it is highly desirable to take maximum possible advantage of reduced temperature in order to increase test Reynolds number. As can be seen from

figure 4, the changes in Reynolds number per degree Kelvin change in stagnation temperature approaches 2% at the lower temperatures. An additional incentive to operate at lower temperatures is the reduction in fan-drive power and an attendant reduction in the amount of liquid nitrogen required for cooling.

Early theoretical studies of the minimum operating temperature were based on the assumption that condensation of the stream must be avoided under the most adverse flow conditions existing in the test section. Condensation is most likely to begin in the high local Mach number region over the model being tested where the pressure of the gas is at a minimum. Under the assumption that the gas is in static equilibrium at this low pressure, it can be shown that liquefaction of the stream will begin when the temperature associated with the low-pressure region just matches the saturated vapor temperature. Thus, under the assumption that condensation must be avoided, there exists for a given stagnation pressure and temperature a maximum local Mach number which must not be exceeded.

As noted in reference 7, the assumptions made for the early look at minimum operating temperature were recognized as overly conservative. Based on theoretical considerations as well as on experimental results (see refs. 11 and 12) it is apparent that temperatures considerably lower than those based on maximum local Mach number considerations can, under certain circumstances, be used and still avoid any effects of condensation on the data.

4. THE LANGLEY 1/3-METER TRANSONIC CRYOGENIC TUNNEL

Following the successful completion of the low-speed tunnel work described in references 7 and 8, it was decided to construct a relatively small continuous-flow fan-driven transonic pressure tunnel in order to extend the design and operational experience to the pressure and speed range contemplated for a large high Reynolds number facility. The purposes envisioned for the pilot transonic cryogenic tunnel were to demonstrate in compressible flow that the results obtained when Reynolds number is increased by reducing temperature are equivalent to those obtained when Reynolds number is increased by increasing pressure, to determine experimentally any limitations imposed by liquefaction, to verify engineering concepts with a realistic tunnel configuration, and to provide additional operational experience. Design of the transonic tunnel began in December 1972 and initial operation began in September 1973.

4.1 Description of the Tunnel

The tunnel is a single-return fan-driven tunnel with a slotted, octagonal test section measuring 34 cm from flat to flat. A sketch of the tunnel circuit is shown in figure 5. The fan is driven by a 2.2-MW variable-frequency motor which is capable of operating the tunnel at Mach numbers from about 0.05 to about 1.3 at stagnation pressures from slightly greater than 1 atm to 5 atm over a stagnation temperature range from about 77 K to 350 K. As was the case with the low-speed tunnel described in references 7 and 8, the wide range of operating temperatures is obtained by spraying liquid nitrogen (LN_2) directly

into the tunnel circuit to cool the structure and the gas stream and to remove the heat of compression added to the stream by the drive fan.

Although the test-section width is only 34 cm, the combination of a pressure of 5 atm and cryogenic capability provides a chord Reynolds number of over 10×10^6 at $M_\infty = 1$, which is equivalent to an ambient tunnel having a test section greater than 7 m by 7 m. The range of operating temperature and pressure also provides the opportunity of investigating independently the effects of temperature and pressure over almost a five-to-one range of Reynolds number. A more detailed description of the Langley 1/3-meter transonic cryogenic tunnel and its ancillary equipment can be found in reference 13.

4.2 Experimental Results From the Langley 1/3-Meter Transonic Cryogenic Tunnel

Two types of experimental data are being obtained from the transonic cryogenic tunnel. The first type relates to the operation and performance of the tunnel itself. The data for the most part consist of the usual tunnel calibration information but with particular emphasis being placed on identifying any problems related either to the method of cooling or to the wide range of operating temperature.

The major conclusions with respect to operation and performance to be made after almost 600 hours of running at cryogenic temperatures are as follows:

1. Purging, cooldown, and warmup times are acceptable and can be predicted with good accuracy.
2. Liquid nitrogen requirements for cooldown and running can be predicted with good accuracy.
3. Cooling with liquid nitrogen is practical at the power levels required for transonic testing. Test temperature is easily controlled and good temperature distribution obtained by using a simple nitrogen injection system.
4. Test-section flow quality is good over the entire range of operating conditions.

The experimental data on which these conclusions are based as well as other information related to the operational and performance characteristics of the Langley 1/3-meter transonic cryogenic tunnel have been reported in references 13, 14, and 15 and will not be discussed further in this paper.

In addition to the experimental results related to the operational and performance aspects of the cryogenic tunnel, there have been a series of aerodynamic experiments primarily aimed at determining the validity and practicality of the cryogenic concept in compressible flow. In the following sections will be presented some of the results of these validation experiments.

4.2.1 Two-Dimensional Airfoil Tests

Based on the real-gas studies of reference 10, there is little doubt that airfoil pressure distributions measured for given values of Reynolds number and Mach number should be the same at cryogenic and ambient temperature conditions. However, in order to provide experimental verification of this equivalence, the

pressure distribution on a two-dimensional airfoil has been measured in the Langley 1/3-meter transonic cryogenic tunnel at ambient and cryogenic temperatures under conditions of constant Reynolds number and Mach number.

A modified NACA 0012-64 airfoil having a 13.72-cm chord was used for the two-dimensional airfoil pressure tests. The airfoil spanned the octagonal test section and was fastened to the walls in such a way that incidence could be varied. An airfoil somewhat larger than would normally be tested in this size tunnel was selected in order to allow for more accurate model construction, a reasonable number of pressure orifices, and higher chord Reynolds number. The fact that the relatively high ratio of chord to tunnel height might result in wall-induced interference was of no particular concern since the tests were being made only to determine whether the airfoil pressure distribution was modified in any way by real-gas effects associated with testing at cryogenic temperatures. The pressure distribution data should therefore be looked at from the point of view of agreement or lack of agreement between data obtained at ambient and cryogenic conditions and the results used only as an indication of the validity of the cryogenic concept. The conditions selected to insure a valid and critical cryogenic evaluation were:

1. Ambient and cryogenic temperature tests were made in the same tunnel on the same model at the same Mach number and Reynolds number.
2. The airfoil was tested with free transition to allow any possible temperature effect on boundary-layer development.
3. The symmetrical airfoil was tested at zero incidence to eliminate any shape or incidence change due to the dynamic-pressure differences between the ambient and cryogenic temperature conditions.
4. Free-stream Mach number exceeded the Mach number normal to the leading edge of typical near-sonic transport designs.

A comparison of the pressure distribution for ambient and cryogenic temperature tests at free-stream Mach numbers of 0.75 and 0.85 are shown in figure 6. For this comparison, the same chord Reynolds number was obtained at each temperature and constant Mach number by an appropriate adjustment of pressure with temperature. As can be seen, there is excellent agreement at both Mach numbers between the pressure distributions obtained at ambient and cryogenic conditions. This is considered to be a valid check in view of the large variation in the gas properties over this large temperature and pressure range. In addition, this agreement is particularly significant with regard to setting tunnel conditions when one considers, for example, the large variation of the speed of sound with temperature and the sensitivity of the airfoil pressure distribution to changes in Mach number.

The distribution at $M_\infty = 0.85$ is of perhaps greater significance since the pressure distribution shows the flow to be supersonic over a large portion of the airfoil, reaching a local Mach number of about 1.22 just ahead of the strong recompression shock. This type of flow, typical of supercritical flows, should be extremely sensitive to any anomalous behavior of the test gas due to operation at cryogenic temperatures. The almost perfect agreement in the pressure distributions provides experimental confirmation that nitrogen at cryogenic temperatures behaves like a perfect gas and is therefore a valid transonic test gas as predicted by the real-gas studies.

4.2.2 Three-Dimensional Model Tests

Three-dimensional model tests have been made in the transonic cryogenic tunnel on a delta-wing model with a sharp leading edge, an aspect ratio of 1.07, and a sweep of 75°. The overall length of the model was 20 cm and the maximum span was 10.4 cm.

The purpose of the three-dimensional model tests were (1) to investigate any possible effects of testing at cryogenic temperatures on the aerodynamic characteristics of a configuration having flow characterized by a separation-induced leading-edge vortex, and (2) to obtain experience at cryogenic temperatures with an electrically heated internal strain-gage balance and the accompanying sting, supporting strut, and angle-of-attack measuring device. (Similar tests with satisfactory results had been made previously in the low-speed cryogenic tunnel at Langley with a water-heated balance and the results reported in reference 8.)

The results show that flows with leading-edge vortex effects are duplicated properly at cryogenic temperatures.

An example of the results which have been obtained on the delta-wing model and reported in reference 16 are presented in figure 7 which shows the variation of pitching-moment, drag, and lift-force coefficients with angle of attack at both ambient and cryogenic temperatures for a Mach number of 0.8. The circular symbols indicate experimental results obtained at a stagnation pressure of 4.6 atm and at a stagnation temperature of about 301 K. The square symbols are data taken at a stagnation pressure of 1.2 atm and at a stagnation temperature of 114 K. The Reynolds number, based on mean geometric chord, was 8.5×10^6 for both sets of data. As can be seen, there is good agreement between the experimental results obtained at ambient and cryogenic temperatures.

The three-dimensional model results provide additional evidence that cryogenic nitrogen is a valid test gas even under conditions of separated and reattached (vortex) flow. In addition, there has been no indication of any major problem areas associated with obtaining angle-of-attack or strain-gage balance measurements at cryogenic temperatures.

5. FUTURE PLANS

In addition to being used to verify the validity of the cryogenic wind-tunnel concept and providing more than 600 hours of experience in the operation of a fan-driven cryogenic tunnel, the 1/3-meter tunnel is being used for aerodynamic research in several areas where either the very high unit Reynolds number ($R/m \approx 3 \times 10^8$ at $M_\infty = 1$) or the 25 to 1 range of Reynolds number is required. Some of the future plans for this unique facility are shown in the sketch presented in figure 8 and described in the following sections.

5.1 Two-Dimensional Test Section

Because of the renewed interest in airfoil research and the sensitivity of many of the advanced airfoils to Reynolds number, a two-dimensional test-section leg has been constructed and is being installed in the Langley transonic cryogenic tunnel. The floor and ceiling of the 20- by 60-cm test section are slotted and there is provision for sidewall suction near the model as well as removal of the sidewall boundary layer just ahead of the model.

Pressure orifices on the model and a wake survey device will be used to provide the test data. In addition, a schlieren system is provided to allow for visual observation of the flow field. This new test-section leg will provide a unique facility for fundamental fluid-dynamics research and airfoil development at test Reynolds numbers of up to 50 million on a two-dimensional airfoil having a 15-cm chord.

5.2 Self-Streamlining Two-Dimensional Test Section

A two-dimensional self-streamlining flexible-wall test-section leg is being designed for the 1/3-meter tunnel based on the work by Goodyer and coworkers at the University of Southampton. (See refs. 17 and 18.) Initially, the test section will be used for testing in flows where the Mach number at the walls never exceeds unity. By permitting increased chord length, the flexible-wall test section will allow testing under interference-free conditions at chord Reynolds numbers approaching 100 million.

5.3 Magnetic Suspension and Balance System

The reduction in model loads made possible by the cryogenic wind-tunnel concept and the reduction in the size of the coils used in a magnetic suspension and balance system made possible by superconductor technology makes the combination of these two concepts an attractive means of providing high Reynolds number test capability free from support interference. In such a facility, it will be possible to test free of support interference effects as well as to determine the magnitude of such effects by direct comparison with data obtained by using conventional model support systems. The demonstrated ease and rapidity with which the orientation of the model may be changed with the magnetic suspension system while keeping the model in the center of the test section will facilitate the rapid acquisition of the aerodynamic data which is a desirable feature of any high Reynolds number tunnel. In addition, the retrieval of the model from the test section of a cryogenic tunnel for model configuration changes would be a simple operation with a magnetic-suspension and balance system.

Because of the many advantages offered by a magnetic-suspension and balance system, NASA has supported for several years both in-house and sponsored research in this area. Significant accomplishments resulting from NASA sponsored research include the development of an electromagnetic position sensor at the Aerophysics Laboratory of the Massachusetts Institute of Technology

(ref. 19) and the development of an all-superconductor magnetic-suspension and balance system for aerodynamic testing at the Research Laboratories for the Engineering Sciences at the University of Virginia (ref. 20).

Additional studies are being made at both Langley and the University of Virginia with the aim of building a six-component superconducting magnetic suspension and balance system to be used in conjunction with an interchangeable test-section leg for the Langley 1/3-meter transonic cryogenic tunnel (ref. 21). Current plans are for the test section of this leg to be octagonal in cross section and to measure approximately 0.45 m from flat to flat. The combination of 5 atmospheres operating pressure and cryogenic temperatures will result in test Reynolds numbers of about 15 million.

6. CONCLUDING REMARKS

Based on theoretical studies and experience with a low-speed cryogenic tunnel and with the Langley 1/3-meter transonic cryogenic tunnel, the cryogenic concept has been shown to offer many advantages with respect to the attainment of full-scale Reynolds number at reasonable levels of dynamic pressure in a ground-based facility. The unique modes of operation which are available only in a pressurized cryogenic tunnel make possible for the first time the separation of Mach number, Reynolds number, and aeroelastic effects. By reducing the drive-power requirements to a level where a conventional fan-drive system may be used, the cryogenic concept makes possible a tunnel with high productivity and run times sufficiently long to allow for all types of tests at reduced capital costs, and for equal amounts of testing, reduced total energy consumption in comparison with other tunnel concepts.

7. REFERENCES

1. Heppe, Richard R.; O'Laughlin, B. D.; and Celniker, Leo: New Aeronautical Facilities — We Need Them Now. Astronaut. & Aeronaut., Vol. 6, No. 3, Mar. 1968, pp. 42-54.

2. Hills, R.: The Need for a Large Transonic Wind Tunnel in Europe: A Summary of the Report of an AGARD Working Group (LaWs). AIAA Paper No. 74-630, July 1974.

3. Pozniak, O. M.: Investigation Into the Use of Freon 12 as a Working Medium in a High-Speed Wind Tunnel. Note No. 72, Coll. Aeronaut., Cranfield (Engl.), Nov. 1957.

4. Treon, Stuart L.; Hofstetter, William R.; and Abbott, Frank T., Jr.: On the Use of Freon-12 for Increasing Reynolds Number in Wind-Tunnel Testing of Three-Dimensional Aircraft Models at Subcritical and Supercritical Mach Numbers. Facilities and Techniques for Aerodynamic Testing at Transonic Speeds and High Reynolds Number, AGARD CP No. 83, Aug. 1971, pp. 27-1 — 27-8.

5. Baals, Donald D.; and Stokes, George M.: A Facility Concept for High Reynolds Number Testing at Transonic Speeds. Facilities and Techniques for Aerodynamic Testing at Transonic Speeds and High Reynolds Number, AGARD CP No. 83, Aug. 1971, pp. 28-1 — 28-12.

6. Smelt, R.: Power Economy in High-Speed Wind Tunnels by Choice of Working Fluid and Temperature. Rep. No. Aero. 2081, Brit. R.A.E., Aug. 1945.

7. Goodyer, Michael J.; and Kilgore, Robert A.: The High Reynolds Number Cryogenic Wind Tunnel. AIAA Paper No. 72-995, Sept. 1972.

8. Kilgore, Robert A.; Goodyer, Michael J.; Adcock, Jerry B.; and Davenport, Edwin E.: The Cryogenic Wind-Tunnel Concept for High Reynolds Number Testing. NASA TN D-7762, 1974.

9. Polhamus, E. C.; Kilgore, R. A.; Adcock, J. B.; and Ray, E. J.: The Langley Cryogenic High Reynolds Number Wind-Tunnel Program. Astronaut. and Aeronaut., Vol. 12, No. 10, Oct. 1974, pp. 30-40.

10. Adcock, Jerry B.; Kilgore, Robert A.; and Ray, Edward J.: Cryogenic Nitrogen as a Transonic Wind-Tunnel Test Gas. AIAA Paper No. 75-143, Jan. 1975.

11. Hall, Robert M.: Preliminary Study of the Minimum Temperatures for Valid Testing in a Cryogenic Wind Tunnel. NASA TM X-72700, 1975.

12. Hall, Robert M.: Further Study of the Minimum Temperatures for Valid Testing in a Cryogenic Wind Tunnel. NASA TM X-72924, 1976.

13. Kilgore, Robert A.: Design Features and Operational Characteristics of the Langley Pilot Transonic Cryogenic Tunnel. NASA TM X-72012, 1974.

14. Kilgore, Robert A.; Adcock, Jerry B.; and Ray, Edward J.: Simulation of Flight Test Conditions in the Langley Pilot Transonic Cryogenic Tunnel. NASA TN D-7811, 1974.

15. Ray, Edward J.; Kilgore, Robert A.; and Adcock, Jerry B.: Analysis of Validation Tests of the Langley Pilot Transonic Cryogenic Tunnel. NASA TN D-7828, 1975.

16. Kilgore, Robert A.; and Davenport, Edwin E.: Static Force Tests of a Sharp Leading-Edge Delta-Wing Model at Ambient and Cryogenic Temperatures With a Description of the Apparatus Employed. NASA TM X-73901, June 1976.

17. Goodyer, M. J.: A Low-Speed Self-Streamlining Wind Tunnel. Paper 13 of AGARD CP-174, Proceedings of the AGARD Conference on Wind Tunnel Design and Testing Techniques, London, U.K., 6-8 Oct. 1975.

18. Judd, M.; Wolf, S. W. D.; and Goodyer, M. J.: Analytical Work in Support of the Design and Operation of Two-Dimensional Self-Streamlining Test Sections. NASA CR-145019, 1976.

19. Stephens, Timothy: Design, Construction, and Evaluation of a Magnetic Suspension and Balance System for Wind Tunnels. NASA CR-66903, 1969.

20. Humphris, R. R., et al.: Performance Characteristics of the U. Va. Superconducting Wind Tunnel Balance. Paper presented at the 1974 Applied Superconductivity Conference.

21. Zapata, Ricardo N.: Magnetic Suspension Techniques for Large-Scale Aerodynamic Testing. Paper 39 of AGARD CP-174, Proceedings of the AGARD Conference on Wind Tunnel Design and Testing Techniques, London, U.K., 6-8 Oct. 1975.

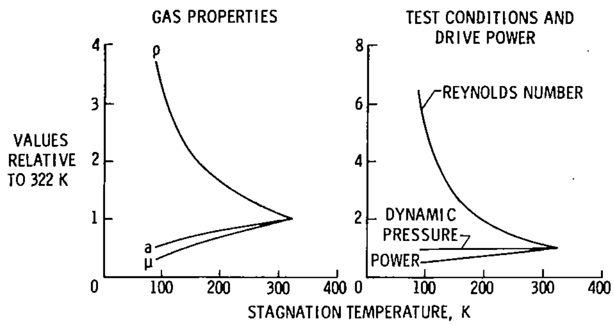

Figure 1. Effect of temperature reduction on the gas properties, test conditions, and drive power. M_∞ = 1.0; constant stagnation pressure and tunnel size.

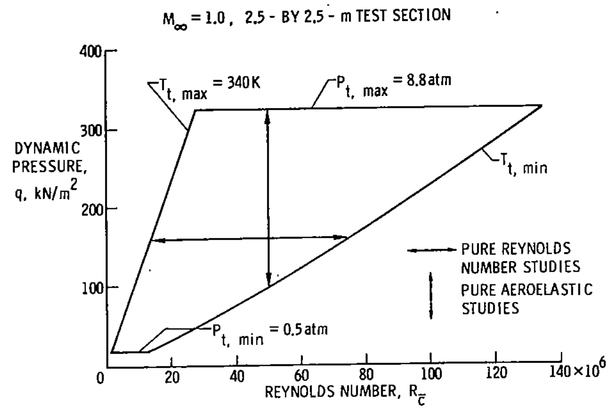

Figure 3. Constant Mach number operating envelope for cryogenic nitrogen tunnel.

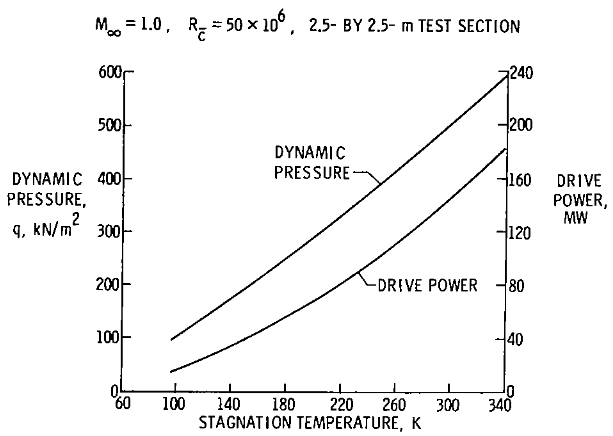

Figure 2. Effect of temperature reduction on dynamic pressure and drive power.

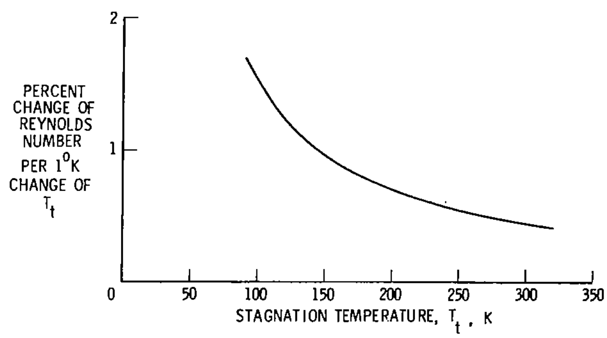

Figure 4. Change in Reynolds number per 1° change in stagnation temperature.

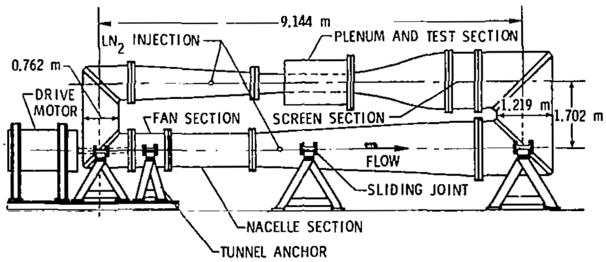

Figure 5. Layout of Langley 1/3-meter transonic cryogenic tunnel.

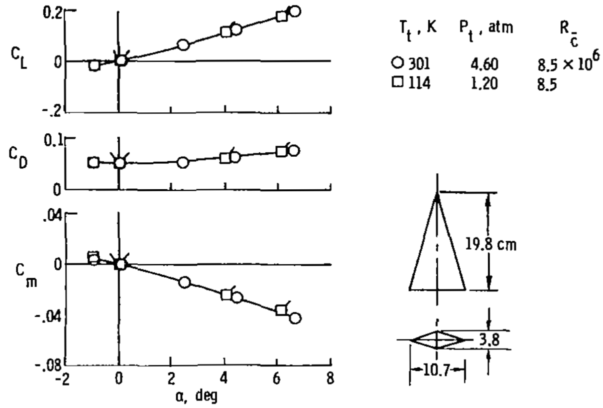

Figure 7. Static aerodynamic characteristics of a delta-wing model at ambient and cryogenic temperatures as a function of angle of attack. $M_\infty = 0.80$; $R_{\bar{c}} = 8.5 \times 10^6$.

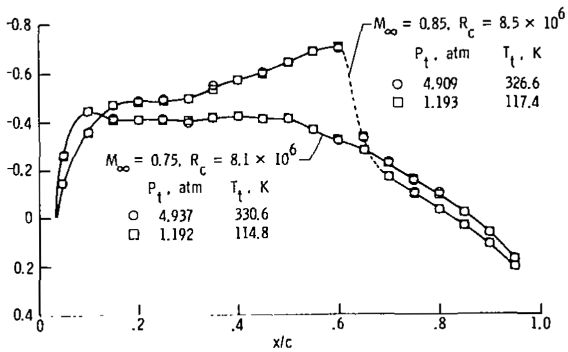

Figure 6. Comparison of the pressure distributions for a symmetrical two-dimensional airfoil obtained at ambient and cryogenic conditions. $\alpha = 0°$.

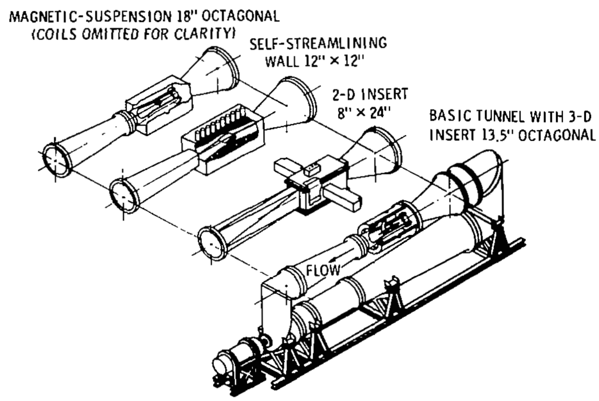

Figure 8. Interchangeable test sections of the Langley 1/3-meter transonic cryogenic tunnel.